Reconfigurable orbital angular momentum and polarization manipulation of 100 Gbit/s QPSK data channels

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We demonstrate reconfigurable orbital angular momentum (OAM) and polarization manipulation of OAM- and polarization-multiplexed 100 Gbit/s quadrature phase shift keying (QPSK) data channels. Each data channel’s OAM value and its polarization state can be arbitrarily changed by taking advantage of the unique wavefront profile of OAM beams using liquid crystal on silicon-based spatial light modulators. The manipulation operation introduces a power penalty of <1 dB for 100 Gbit/s QPSK signals. © 2013 Optical Society of America

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Space-division multiplexing (SDM) has received much interest recently due to its potential for increasing data-transmission capacity and spectral efficiency by multiplexing many independent data streams on the same spatial channel [1]. One method to achieve SDM is to use multiple laser beams carrying orbital angular momentum (OAM) [2]. A beam that contains OAM is characterized by a wavefront whose phase varies linearly with the azimuthal angle to complete an integral multiple (\(\ell\)) of 2\(\pi\) upon a full rotation. This twisting of the phase into a corkscrew shape results in a doughnut-like ring intensity profile [3]. Recent work has reported a 2.56 Tbit/s free-space optical data transmission using OAM, in which multiple polarization-multiplexed beams located at the same wavelength were transmitted simultaneously [4]. Moreover, terabit/s fiber-based OAM transmission using a vortex fiber has been achieved [5].

There is a discrete series of OAM values for the rate of phase-front twisting that can be created, such that each data-carrying OAM beam is theoretically orthogonal to all other OAM beams. Orthogonality enables multiple, spatially overlapping beams of different OAM values to be (de)multiplexed. By multiplexing multiple beams located on the same wavelength, the total system capacity and spectral efficiency are increased [2–4].

Existing reports on OAM-based communication systems have generally involved static point-to-point links [3–6]. Historically, wavelength-dependent routing functions have enabled dramatic networking advances in wavelength-division multiplexing (WDM) systems [7]. It might prove useful to enable reconfigurable networking functions in OAM-based multiuser systems for which the OAM value of the beam determines the routing. Recent reports have demonstrated mode-based switching and routing [8–10].

Moreover, given the desire for increased capacity and spectral efficiency, polarization multiplexing has become well accepted in the optical communications community [11–14]. Although basic OAM-based networking functions have been demonstrated, we are not aware of any reports of reconfigurable manipulation of independent data channels that reside on two orthogonal polarizations.

In this Letter, we demonstrate the reconfigurable OAM and polarization manipulation of OAM-multiplexed 100 Gbit/s quadrature phase shift keying (QPSK) data channels [15]. Given two input data channels, we show that each data channel’s OAM value, as well as its polarization state, can be arbitrarily changed using liquid crystal on silicon-based spatial light modulators (SLM) by taking advantage of the unique wavefront profile of OAM beams. The manipulation operation introduces a power penalty of <1 dB for 100 Gbit/s QPSK signals. The minimum mode spacing for OAM-multiplexed inputs and the imperfect multiplexing tolerance of polarization-multiplexed inputs are investigated.

The concept of OAM and polarization manipulation is shown in Fig. 1. For the input data channels that are OAM and/or polarization multiplexed, the goal is to be able to shift the OAM charge and meanwhile change the polarization state of each channel in the optical domain, so that...
the two data channels are carried either on the same OAM beam with two orthogonal polarizations or carried on two different OAM beams with the same polarization.

The procedures of the manipulation are described in Fig. 2. Figure 2(a) depicts the conversion from a polarization-multiplexed signal to an OAM-multiplexed signal. We first separate the two polarization states using a polarization beam splitter (PBS). The OAM beam on one of two polarizations is downconverted into a Gaussian beam [i.e., the OAM charge is shifted from +ℓ to 0 by applying a conjugated spiral phase pattern with a charge of −ℓ, as shown in Fig. 3(a)]. (Strictly, the downconverted beam is a Gaussian beam plus several ring tails.) The beam on the other polarization is polarization-rotated by 90°, transforming its polarization to that of the downconverted beam. In the next step, the two beams are spatially multiplexed. Meanwhile, we shift the OAM charge of each beam to a different number. This is achieved by using a designed phase hologram, as shown in Fig. 3(b). The hologram uses different phase gratings in the inner region and in the outer region, so that they have different diffraction angles. When the two beams (downconverted beam and the other OAM beam) are launched onto the hologram with different angles, the inner region of the hologram diffracts the downconverted beam (a dot), while the second beam (ring-shaped OAM beam) is diffracted by the outer region. By controlling the grating periods of the two regions, the diffraction angles can be designed to make the two beams emerge propagating coaxially. Meanwhile, we can apply a spiral phase pattern superimposed with the grating, and the beams can be converted to different ℓ values at the first diffraction order. As a result, the polarization-multiplexed signal is converted to an OAM-multiplexed signal. Here we note that this process of differentially treating an OAM beam and a non-OAM beam is approximate because we ignore the tails of the rings. Therefore, it practically requires a minimum spacing between the ℓ of the two beams. On the other hand, when the input signal is OAM-multiplexed with the same polarization, as shown in Fig. 2(b), the first step is the downconversion, where one of the beams is converted into a Gaussian beam, and the other remains ring-shaped, as shown in Fig. 3(a). Subsequently, we launch these two beams onto a similar hologram including two different regions, with the downconverted beam reflected by the inner region and the ring-shaped beam reflected by the outer region. Consequently, the two beams are diffracted to different directions (demultiplexed), as shown in Fig. 3(c). Accordingly, we can also apply spiral phase patterns superimposed with the grating to shift the OAM charge of the beam to a different number. In this case, one of the two separated beams is polarization rotated and multiplexed with the other beam using a PBS, achieving a polarization-multiplexed signal.

The schematic overview of the experimental setup of OAM and polarization switching of two data channels is shown in Fig. 4. An external cavity laser with a linewidth of ~100 kHz is modulated by an I/Q modulator driven by two 50 Gbit/s binary signals to generate 100 Gbit/s QPSK signals. The data sequence that we used involves 2^21−1 random pseudo binary sequences. The generated QPSK signal is split into two decorrelated copies, which are launched onto a SLM. The SLM, loaded with a spiral phase hologram, converts the regular beam from the fiber collimator into an OAM beam. The light path ① in Fig. 4 prepares an OAM-multiplexed signal, and the path ② prepares a polarization multiplexed signal. For case ①, where the two data channels have two different OAM charges (e.g., ℓ1, ℓ2) but the same polarization, they are launched onto SLM1 loaded with a spiral phase pattern of −ℓ2, which performs the downconversion. The downconverted beam (indicated by the dash line) and the OAM beam are separated by SLM2, which is loaded with the designed phase grating holograms. One of these is polarization rotated using a half-wave plate. Then they are both polarization multiplexed, using a PBS. For case ②, the two polarizations are separated when passing through the PBS. One of the beams is downconverted by SLM1, while the other beam is directly launched onto SLM2 after polarization rotation. SLM2 multiplexes these two beams and shifts the OAM charge of each, so that a conversion from the polarization-multiplexed signal to the OAM-multiplexed signal is achieved. To detect the data on each channel, SLM3 is used to convert the OAM beam into a Gaussian beam. Following this, the beam is
coupled into a single-mode fiber and sent to a coherent receiver for bit error rate (BER) and constellation analysis.

Figure 5(a) depicts the conversion from two polarization-multiplexed OAM beams \( (\ell_1 = \ell_2 = +2) \) to two OAM-multiplexed beams \( (\ell_1 = +3 \text{ and } \ell_2 = +6) \) on the same polarization. Figure 5(b) illustrates all of the recorded images (intensity profiles) of the input and output beams before and after the manipulation. Two OAM beams \( (\ell = +2) \) are polarization multiplexed, as shown in Fig. 5(b). After passing through the system, a superposition of two OAM beams with \( \ell = +3 \) and \( \ell = +6 \) is obtained, as shown in the right panel of Fig. 5(b). The on-axis interference patterns of the input and output beams with a plane wave (approximated by an expanded Gaussian beam) are illustrated in Fig. 5(c). The interferograms show that each of the two input beams has a helical phase front with a charge of +2. One of the output beams has a spiral phase front with a charge of +3, and the other has a spiral charge of +6, which indicate that the OAM beams are converted as expected. The measured BER curves in Fig. 4(d) indicate a power penalty of \( \sim 0.4 \) dB at a BER of \( 3.8 \times 10^{-3} \).

We also demonstrate the potential reconfigurability of the scheme by demonstrating the results of different manipulations on different input signals, as shown in Fig. 6. For a polarization-multiplexed signal, we can shift the charge of the OAM beam on one [Fig. 6(a1)] or both polarizations [Fig. 6(a2)]. The polarization state and OAM charge of each channel can be changed by using the setup, as shown in Fig. 6(a3). Figures 6(a4) and 6(a5) show that for the input OAM-multiplexed signal, the polarization state and OAM charge also can be converted at the same time. All of the above conversions are achieved by using the proposed scheme. The measured BER curves for the manipulation of Figs. 6(a1) and 6(a2) are shown in Figs. 7(a1) and 7(a2), respectively. OSNR penalties of \( < 1 \) dB are observed in both cases. The recovered constellations of 100 Gbit/s QPSK signal of Figs. 6(a1) and 6(a2) are shown in Figs. 7(b1) and 7(b2), respectively.

The demultiplexing stage in a conversion from an OAM-multiplexed signal to a polarization multiplexed signal [Fig. 8(a)] may introduce crosstalk between two data channels due to insufficient separation between the center dot and the ring-shaped beam. To investigate
the effect, we measured the dependence of the crosstalk between two channels on the mode spacing between the two OAM beams. Here the crosstalk is defined as the ratio of the received power from the desired channel to the received power from the other channel. Figure 8(a) shows the measured BER of OAM mode spacing in a conversion from an OAM-multiplexed signal to a polarization-multiplexed signal. The results suggest that for an OAM-multiplexed signal, an OAM charge spacing of \( > 3 \) can achieve a BER below the 3.8 \times 10^{-3} level, which is the threshold that can be corrected using forward error correction coding.

Similarly, in a conversion from a polarization-multiplexed signal to an OAM-multiplexed signal, the imperfect multiplexing (i.e., two polarization states are not orthogonal) also may cause performance degradation. We investigate the crosstalk between two channels after conversion as a function of the angle between the polarization states of the two multiplexed channels. Figure 8(b) shows the tolerance of the scheme to imperfect polarization multiplexing. Both BER and crosstalk varies with the multiplexing angle between two linearly polarized channels. We note that if the polarization-multiplexed signals pass through a medium with polarization mode dispersion, additional crosstalk between the two channels could be induced due to the PBS in the manipulation process.

In conclusion, this study demonstrates OAM and polarization manipulation for polarization- and OAM-multiplexed 100 Gbits/s QPSK data channels. Reconfigurability is shown by demonstrating different conversion functions. The mode spacing and polarization-multiplexing angle tolerances also are investigated.

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References